Effects of Small-scale Bathymetric Roughness on the Global Internal Wave Field

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LONG-TERM GOALS

The small-scale roughness properties of the seafloor are increasingly being recognized as critical parameters in determining important processes in physical oceanography. For instance, *in situ* observations (e.g., Polzin et al., 1997) find that mixing levels are greatly elevated in regions of rough topography. Gille et al. (2000) demonstrate that mesoscale eddy energy tends to be lower in areas where the bottom is rough (suggesting the possibility that dissipation of eddy energy takes place in such areas), and Egbert and Ray (2003) show that substantial tidal dissipation occurs in such areas. The dissipation is generally thought to arise from the breaking of internal waves generated by flows over the rough seafloor. On the time scales of internal waves, mesoscale eddies and the general circulation can be regarded as steady, while tides are oscillatory. The physics of linear internal wave generation is different for these two classes of motions (e.g., Bell 1975), but for both types of flows the wave generation is strongly dependent on the horizontal and vertical scales inherent in the bottom topography. Using the classical formulation for lee waves (e.g., Cushman-Roisin, 1994, St. Laurent, 1999), one can argue that horizontal wavelengths ranging from ~60 m to 6 km generate internal waves when forced by steady flows. Features typical of abyssal hill morphology (e.g., 50 m height over 1 km horizontal scale) will generate a significant vertical internal wave energy flux. High-resolution regional models (e.g., Zilberman and Merrifield, 2006) demonstrate that topographic information on scales of order 3 km are also important for internal tides. Non-linear effects may be important as well, as some oceanographers (e.g., Thurnherr and Richards, 2001; Thurnherr et al., 2002; Thurnherr and Speer, 2003; St. Laurent and Thurherr, 2007) have argued from observational data that turbulence associated with hydraulic jumps occurs in area of rough topography when the Froude number exceeds an order one threshold. This occurs when topography over scales of 1 km exceeds 20 m in height, which is typically the case for abyssal hill morphology.

A significant dilemma for physical oceanographers studying these processes is that the kind of bathymetric resolution required to model these processes over entire ocean basins are not available, nor will be any time soon. Acoustic bathymetric data, which can achieve lateral resolutions of 0.1-0.2 km, presently cover only a few percent of the ocean floor beyond the exclusive economic zones in coastal

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areas. A complete swath survey of all the deep oceans would take ~200 years of ship time at a cost of billions of dollars (Carron et al., 2001). The most comprehensive determination of bathymetry world-wide is the Smith and Sandwell (1994; 1997; 2004) model derived from satellite altimetry data combined with data from ship soundings, but the resolution of this product is limited to >10 km in the deep ocean. We seek to resolve this dilemma through a novel approach of relating the texture of satellite altimeter data to seafloor roughness characteristics. We will then address issues of importance to the Navy with tide models that utilize this information, either by directly resolving internal wave generation over the rough seafloor, or by parameterizing the dissipation of these internal waves. In particular, we will investigate internal wave generation in a global baroclinic tide model, and we will investigate the effect of parameterized dissipation over rough topography in both barotropic and baroclinic global tide models.

OBJECTIVES

Our main objectives are to characterize seafloor roughness from satellite altimetry data and investigate the impact of rough topography on the global internal tide field. Specific tasks include:

(1) Full spectral characterization of altimeter noise world-wide and transfer function for predicting resultant noise in the gravity signal via the processing path.

(2) Advance the study of the relationship between gravity and abyssal hill fabric.

(3) Generate map of abyssal hill roughness parameters across the ocean basins.

(4) Determine the location of dissipation in global baroclinic tide models.

(5) Parameterize unresolved topographic wave drag in global tide models.

(6) Determine the impact of better roughness estimates on the resolved generation of internal tides in a global model.

APPROACH

Satellite altimetry data and the derived gravitational field (Fig. 1) may make it possible to infer seafloor statistical parameters over entire ocean basins, and are the focus of tasks 1-3 noted above. While it is difficult, owing to the limits of upward continuation of gravity in the deep ocean, for seafloor features < ~10 km scale to be distinguished individually in the altimetry data, the aggregate fabric of small-scale features, such as abyssal hill morphology, can have a quantifiable effect on the gravity fabric (Goff and Smith, 2003; Goff et al., 2004). Our governing hypothesis, which is partially confirmed by these prior results, is that an empirical transfer function can be determined which relates the primary attributes of bathymetric and gravity roughness (rms height, characteristic horizontal scales, and fabric orientation) to each other. However, at these limiting scales of altimetry resolution, process filtering (Smith and Sandwell, 1997), which is necessary to convert raw altimetry data into coherent gravity field estimates, and data noise, related both to data uncertainties and oceanographic variability, will also have a significant effect on gravity fabric. These must be fully accounted for.

The Goff and Smith (2003) and Goff (2004) analyses demonstrate clearly the importance of quantifying altimetry noise (Task 1 above) if we are to extract abyssal hill roughness properties from the altimetry data set. Altimetric noise is neither constant nor simple in statistical character. Figure 2 plots the rms difference in the along-track sea surface slope as computed from the version 15.1 altimetric gravity field model of Smith and Sandwell and as measured by the Geosat altimeter during its Geodetic Mission (GM). This rms difference includes the effects of random errors and (non-tidal) time-varying dynamic sea surface slopes, and is an error source in the estimation of gravity (and hence abyssal hill fabric) from altimetry. The 1 to 4 micro-radian (mm per km) sea surface slope errors in Figure 2 can be expected to produce roughly 1 to 4 milliGal errors in gravity. The inference from this plot is that noise strength is regionally variable, and correlated strongly to average sea state and to currents and attendant mesoscale eddy conditions. Thus, not only will the contribution of noise to the gravity roughness be regionally dependent, but we can also expect a non-white statistical character to the altimetry noise, corresponding to the horizontal scales of oceanographic and atmospheric heterogeneities, that will complicate the noise response in the gravity map.

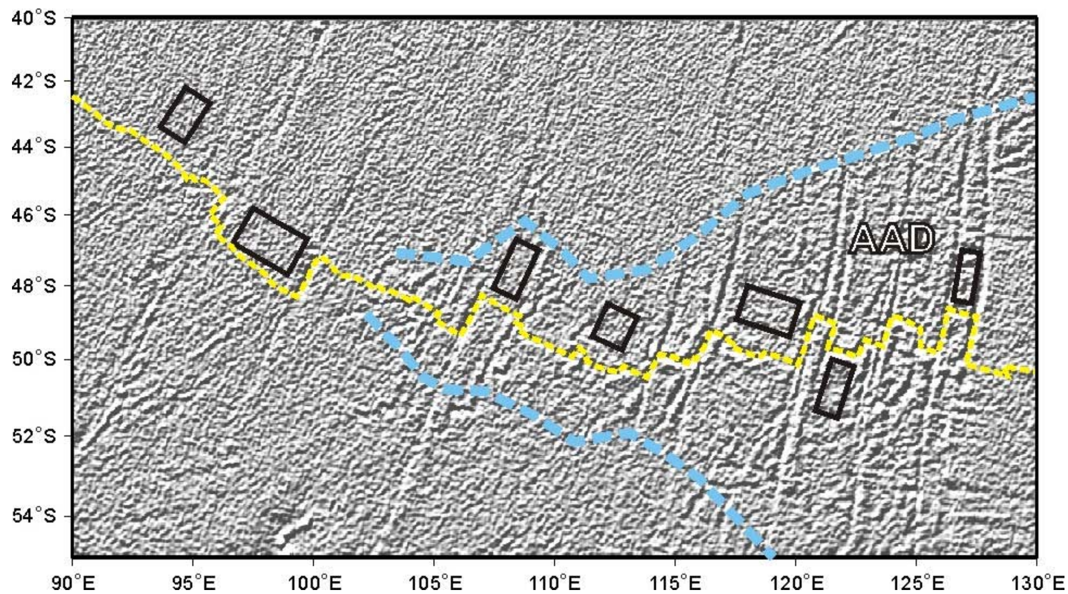

Figure 1. Sun-shaded altimetric gravity field (Sandwell and Smith, 1997), emphasizing roughness, over a portion of the Southeast Indian Ridge (yellow) corresponding to a change in ridge morphology: from an axial high in the west to an axial valley in the east progressing into the Australian-Antarctic Discordance (AAD), and a corresponding change in abyssal hill roughness (Goff et al., 1997). The blue dashed line marks a visually-determined textural boundary off axis. Boxes indicate areas chosen by Goff and Smith (2003) for gravity texture estimation, which demonstrated that the quantitative characterization of gravity texture varied in concert with the abyssal hill roughness.

To characterize noise in the gravity map, we must first characterize noise in the raw altimetry data, prior to the application of the various filtering and processing steps. In our preliminary analyses, we have devised a means of largely isolating the noise by computing and comparing the auto- and cross-covariances of overlapping or closely adjacent parallel altimeter tracks. The overriding assumptions here are that (1) adjacent tracks will be highly correlated with respect to the influence of seafloor morphology on altimetry, but (2) highly decorrelated with respect to noise components, including variations related to mesoscale eddies. The first assumption is justified based on the short distance between adjacent tracks (average ~6 km at the equator, less at higher latitudes) compared to the effective upward continuation distance (~20 km). The second assumption is justified because the minimum time between adjacent tracks (~17 days) is similar to the decorrelation time for mesoscale circulation (~15 days; Traon et al., 1998).

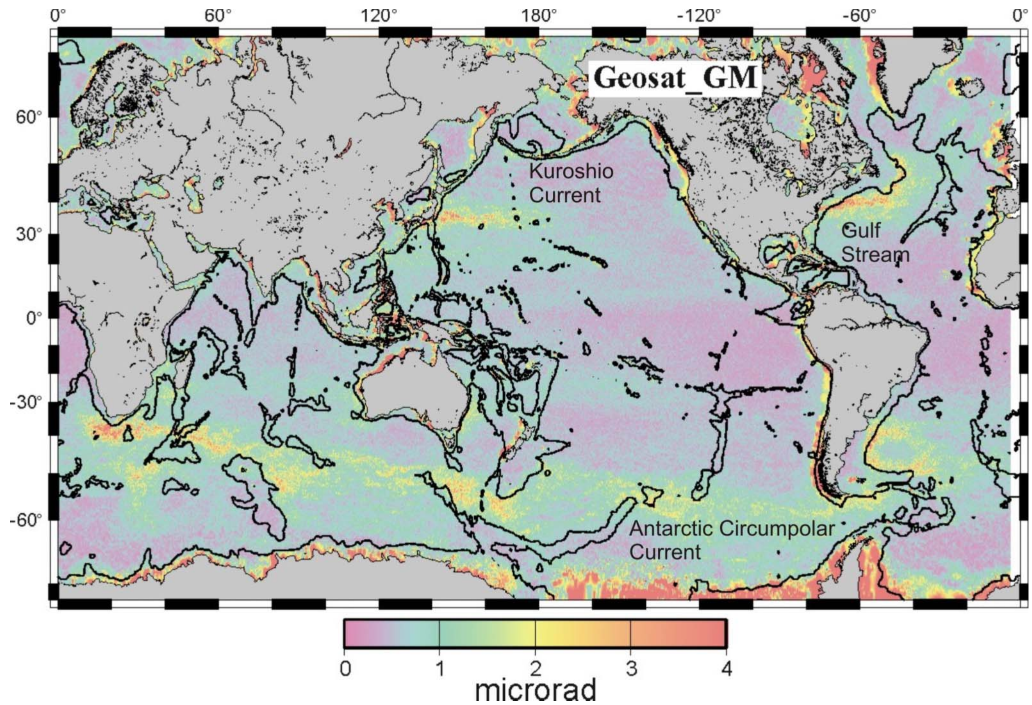

Figure 2. RMS sea surface gradient errors for the altimetry data making up version 15.1 of the Smith and Sandwell gravity model (from David Sandwell, personal comm.). These results are indicative of noise contribution to the gravity data, and demonstrate correlation between physical oceanographic features and altimetry noise.

Approaches for Tasks 2 and 3 will be detailed in later progress reports.

The spatial distribution of dissipation in the ocean is a matter of intense interest in the oceanographic community, including the Navy. Much of the interest stems from the suggestion by Munk and Wunsch (1998) that the strength of the meridional overturning circulation is controlled by ocean mixing. In addition, the general oceanic circulation in models (e.g., Scott and Marotzke 2002) shows a strong sensitivity to the spatial distribution (in both the vertical and horizontal directions) of mixing. Mixing diffusivity κ is related to energy dissipation ε by the relation $\kappa = \Gamma\varepsilon/N^2$, where Γ is an efficiency factor of about 0.2 and N is the Brunt-Vaisala buoyancy frequency (Osborn 1980). Since mixing is connected to dissipation, quantification of mixing in the ocean must consider energy sinks, which balance energy sources in averages taken globally and over long periods of time. Quantification of the sources and sinks of energy for the deep ocean has been studied in earnest in recent years. Wunsch (1998) showed that the winds put approximately 1 TW of energy into the oceanic general circulation, while Alford (2001) showed that winds put about 0.5 TW of energy into the near-inertial internal wave field. The details of how these wind energy inputs are eventually converted into a dissipation are not yet well known. Tides put a total of 3.5 TW into the ocean, and of this about 2.5 TW is dissipated in coastal areas, where tidal velocities are much larger, while 1 TW is dissipated in the open ocean, in regions of rough topography (Egbert and Ray 2003). Although the budget for tidal energy is understood better than for wind-forced motions, important questions about the tidal energy cycle remain.

We will accomplish three tasks (4-6) in this part of the proposed work. In task 4 we will use the global baroclinic tide model of Arbic et al. (2004) to examine whether the dissipation of internal tides generated in the open ocean takes place in coastal areas, in the abyssal parts of the open ocean, or in the thermocline of the open ocean. In tasks 5 and 6 we will use the roughness estimates from our work on tasks 1 to 3 in global tide models. In task 5 we will examine the difference that a better roughness estimate makes on our parameterizations of unresolved topographic wave drag, which are used in both barotropic and baroclinic tide models. In task 6 we will return to global model of the resolved internal tide field, as in task 4, but this time with better estimates of seafloor roughness, which will improve the resolution of high baroclinic modes. An interim roughness map can be produced if the final roughness estimates are not ready by the time we need better roughness estimates in our global tide models.

WORK COMPLETED

This project began funding in June. Over the summer Goff began working with the full Geosat altimetry data set and completed a world-wide analysis of altimetry noise at scales < 50 km (i.e., scales that are of importance to characterizing abyssal hill fabric). These results are detailed below. Arbic has begun formulating his methodology for incorporating small-scale seafloor roughness characterization into his tide modeling.

RESULTS

Initial processing of the altimetry data for noise analysis was focused on removing, as much as possible, the time-invariant component of the altimetry measurements by differencing nearest-neighbor track lines. Given that the effective upward continuation filter scale (~20 km) is large compared with the average track spacing (~6 km at the equator, less at higher latitudes), the residual between two adjacent tracks should be dominated by a time-varying signal. Such variability will presumably be related to oceanographic and atmospheric processes that contribute to uncertainty in measuring the static geoid. Figure 3 displays an example of a altimetry residual profile generated by differencing two tracks that are spaced only ~0.5 km apart. Variations of up to a meter in amplitude over scales > 100 km are prominent. Altimeter variations of these scales were studied extensively by Kuragano and Kamachi (2000), who attributed these features to mesoscale oceanographic circulation. Such features are not, however, of interest here because they do not contribute to gravity roughness on the scales that are important to abyssal hills (i.e., < 50 km). To focus our analysis on those scales, we high-pass filtered the difference function using a 50-km cos**2 filter (Figure 3). We found that this filter scale very effectively separated the time-varying altimeter response into large- and small-scale components; i.e., there is very little power in the spectrum at the filter wavelength, but substantial power at both lower and higher wavelengths. A strong high-frequency noise signal is evident in the filtered residual.

Figure 4 displays the covariance function estimated from the high-pass filtered difference profile shown in Figure 3. We observe two distinct components to the covariance functionality: (1) a "white noise" variance, indicated by the height of the spike that exists between the 0th and 1st lag points, and (2) a correleted component that crosses into negative lag values after ~5 km lag, and then returns to ~0 covariance by ~15 km lag. Initial investigation of the correlated component suggests that it is related to the Kalman filter response that is applied by the altimeter to predictively track the signal. Sudden changes in the signal, such as going from land to sea, or crossing a storm cloud, can lead to fluxtuations in the Kalman response.

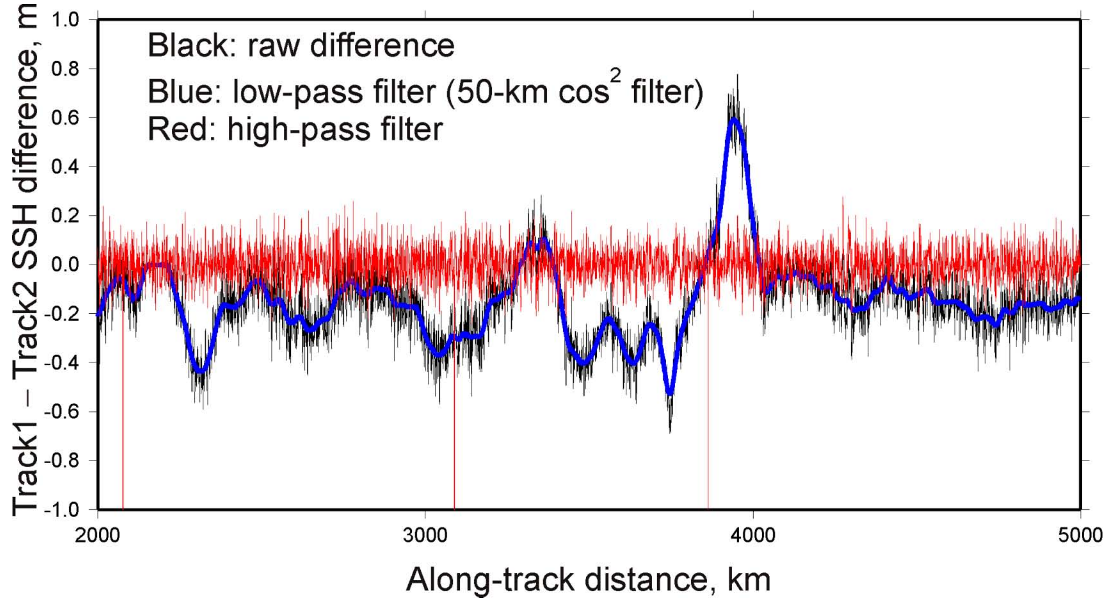

Figure 3. Residual profile between two altimetry tracks (black), and after low-pass (blue) high-pass (red) filtering.

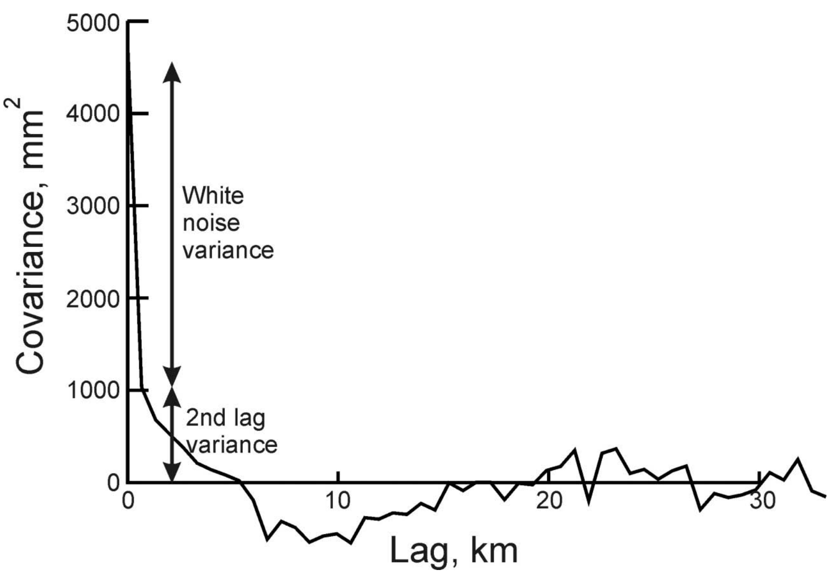

Figure 4. Covariance function computed from the high-pass filtered residual profile shown in Figure 3, illustrating the two primary functional components observed broadly.

The functional structure of these high-pass filtered altimetry difference profiles changes little from one profile to the next, except for the amplitude of the two components. The consistancy of form therefore suggest that small-scale (< 50 km) altimetry noise can be parameterized rather simply by the variance of the two components; i.e., the "white noise variance", which is the height of the 0-lag spike, and the "2nd lag variance" (Figure 4). Figure 5 displays the world-wide distribution of white noise variance computed in this way. Measurements are averaged within 2 by 2 degree bins. There are two observations of note here: (1) that ascending and descending tracks, which are essentially independent data sets, produce very similar results in terms of geographical distribution, and (2) the pattern displayed by both plots is very strongly correlated to significant wave heights (plotted in Figure 6). This correlation is certainly expected, as waves are the primary source of random fluctuations in altimeter data.

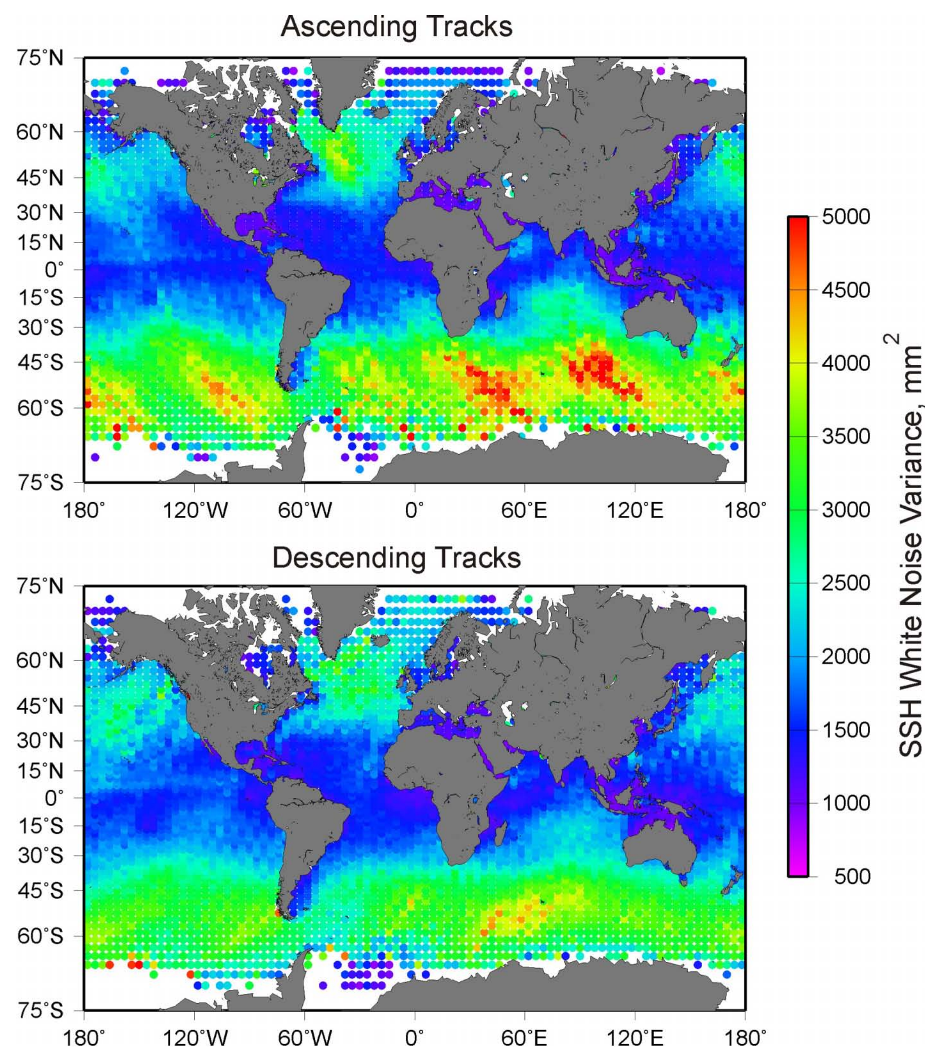

Figure 5. World-wide distribution of white noise variance measurements from high-pass filtered, differenced altimeter tracks, averaged in 2 by 2 degree bins, for both ascending (top) and descending (bottom) tracks.

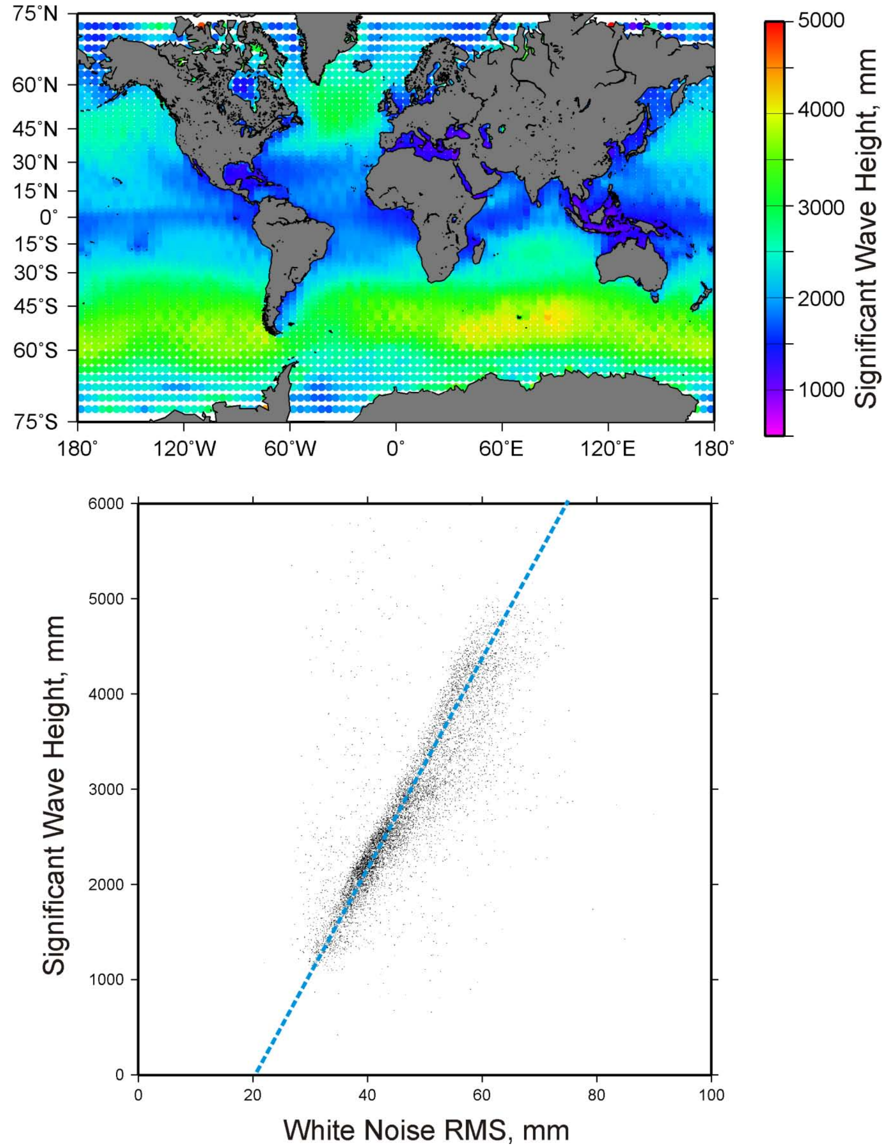

Figure 6. World-wide distribution of significant wave heights (top) and plot of significant wave heights versus white noise RMS in the same 2 by 2 degree bins (bottom). Blue-dashed line illustrates the highly linear nature of the relationship.

The world-wide distribution of second-lag variance is presented in Figure 7. As with the white noise variance, the 2nd-lag variance displays a coherent geographic pattern that is very similar both for ascending and descending tracks. The pattern, however, is quite different from the white noise variance. We qualitatively observe two evident correlations: (1) with sea ice at high latitudes, and (2) with rainfall rates at mid- and low latitudes (e.g., Ikai and Nakamura, 2003). Both ice and rain storms are likely to generate the sort of abrupt change in altimetry response that will cause fluctuations associated with the Kalman filtering.

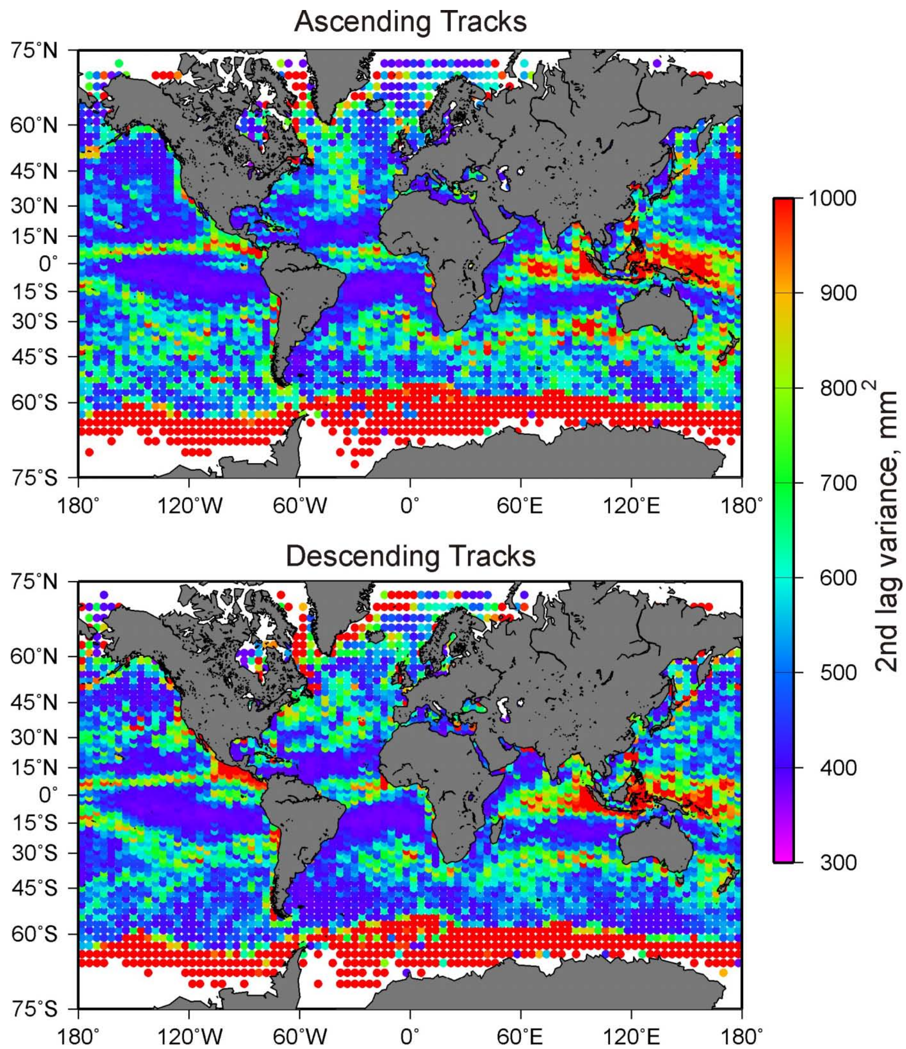

Figure 7. World-wide distribution of 2nd-lag variance measurements from high-pass filtered, differenced altimeter tracks, averaged in 2 by 2 degree bins, for both ascending (top) and descending (bottom) tracks.

IMPACT/APPLICATIONS

With these results, we can now quantitatively characterize short-scale (< 50 km) altimeter noise by region. Our next task will be to transfer the altimetric characterization into a gravity noise characterization, which we plan on doing by generating synthetic noise along all the altimetry tracks, scaled by the relationships shown in Figures 5 and 6, and then processing that "data" through the Smith and Sandwell (1997) methodology for deriving the world-wide gravity map. The resulting map can then be analyzed for global distribution of gravity noise. This will enable us to distinguish what part of the actual gravity fabric is due to noise and which part is influenced by seafloor fabric. An accurate map of small-scale seafloor roughness is expected to have a tremendous impact on oceanographic modeling efforts to predict critical phenomena such as the generation of internal waves and mixing by both tidal and non-tidal (i.e., mesoscale eddy) flows.

RELATED PROJECTS

Arbic has a separate contract with the Naval Research Laboratory (Stennis) to accurately implement global tides in HYCOM. HYCOM is planned to be the next-generation Navy operational global model. Arbic has developed a good working relationship with several of the key HYCOM investigators, and has achieved significant progress in the implementation of tides. The parameterization of topographic wave drag on both tidal and non-tidal motions in HYCOM is expected to be enhanced by the bathymetric roughness work done in this project. In addition, once HYCOM is ready to be used as a tide model, it as well as the Hallberg Iscopycnal Model (Arbic et al., 2004) can be used to accomplish tasks 4-6 of this proposal.

REFERENCES

Alford, M.H., 2001. Internal swell generation: The spatial distribution of energy flux from the wind to mixed-layer near-inertial motions. Journal of Physical Oceanography 31, 2359-2368.

Arbic, B.K., Garner, S.T., Hallberg, R.W., Simmons, H.L., 2004. The accuracy of surface elevations in forward global barotropic and baroclinic tide models. Deep-Sea Research II 51, 3069-3101.

Bell, T.H., 1975. Lee waves in stratified flows with simple harmonic time dependence. Journal of Fluid Mechanics 67, 705-722.

Carron, M. J., P. R. Vogt, Jung, W.-Y., 2001. A proposed international long-term project to systematically map the world's ocean floors from beach to trench: GOMaP (Global Ocean Mapping Program). International Hydrographic Review 2, 49-55.

Cushman-Roisin, B., 1994. Introduction to geophysical fluid dynamics. Prentice-Hall, Englewood Cliffs, 320 pp.

Egbert, G.D., Ray, R.D., 2003. Semi-diurnal and diurnal tidal dissipation from TOPEX/Poseidon altimetry. Geophysical Research Letters 30, 1907, doi:10.1029/2003GL017676.

Gille, S.T., Yale, M.M., Sandwell, D.T., 2000. Global correlation of mesoscale ocean variability with seafloor roughness from satellite altimetry. Geophysical Research Letters 27, 1251-1254.

Goff, J. A., Smith, W. H. F., 2003. The correspondence of altimetric gravity texture to abyssal hill morphology. Geophysical Research Letters 30, doi:10.1029/2003GL018913.

Goff, J. A., Ma, Y., Shah, A., Cochran, J. R., Cochran, Sempéré, J.-C., 1997. Stochastic analysis of seafloor morphology on the flank of the Southeast Indian Ridge: The influence of ridge morphology on the formation of abyssal hills. Journal of Geophysical Research 102, 15,521-15,534.

Goff, J. A., Smith, W. H. F., Marks K. M, 2004. The contributions of abyssal hill morphology and noise to altimetric gravity fabric. Oceanography 17, 24-37.

Ikai, J, Nakamura, K., 2003. Comparison of rain rates of the ocean derived from TRMM microwave imager and precipitation radar. J. Atmos. Oceanic Tech. 20, 1709-1726.

Kuragano, T. Kamachi, M., 2000. Global statistical space-time scales of oceanic variability estimated from TOPEX/POSEIDON altimeter data. J. Geophys. Res. 105, 955-974.

Munk, W., Wunsch, C., 1998: Abyssal recipes II: energetics of tidaland wind mixing. Deep-Sea Res. I 45, 1977-2010.

Osborn, T.R., 1980. Estimates of the local rate of vertical diffusion from dissipation measurements. Journal of Physical Oceanography 10, 83-89.

Polzin, K.L., Toole, J.M., Ledwell, J.R., Schmitt, R.W., 1997. Spatial variability of turbulent mixing in the abyssal ocean. Science 276, 93-96.

Scott, J.R., Marotzke, J., 2002. The location of diapycnal mixing and the meridional overturning circulation. Journal of Physical Oceanography 32, 3578-3595.

St. Laurent, L.C., 1999. Diapycnal advection by double diffusion and turbulence in the ocean. Doctoral dissertation, MIT/WHOI Joint Program, MIT/WHOI 99-12, Cambridge and Woods Hole, MA, 139 pp.
St. Laurent, L.C., Thurnherr, A.M. 2007. Intense mixing of lower thermocline water on the crest of the Mid-Atlantic Ridge. Nature 448, 680-683.
Smith, W. H. F, Sandwell, D. T., 1994. Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. Journal of Geophysical Research 99, 21,803-21,824.
Smith, W. H. F, Sandwell, D. T., 1997. Global seafloor topography from satellite altimetry and ship depth soundings: Evidence for stochastic reheating of the oceanic lithosphere. Science 277, 1956-1962, 1997.
Smith, W. H. F, Sandwell, D. T., 2004. Conventional bathymetry, bathymetry from space, and geodetic altimetry. Oceanography 17, 8-23.
Thurnherr, A.M., Richards, K.J., 2001. Hydrography and high-temperature heat flux of the Rainbow hydrothermal site (36°14'N, Mid-Atlantic Ridge). Journal of Geophysical Research 106, 9411-9426.
Thurnherr, A.M., Speer, K.G., 2003. Boundary mixing and topographic blocking on the Mid-Atlantic Ridge in the South Atlantic. Journal of Physical Oceanography 33, 848-862.
Thurnherr, A.M., Richards, K.J., German, C.R., Lane-Serff, G.F., Speer, K.G., 2002. Flow and mixing in the rift valley of the Mid-Atlantic Ridge. Journal of Physical Oceanography 32, 1763-1778.
Traon, P. Y., Nada, F., Ducet, N., 1998. An improved mapping method of multisatellite altimeter data. Journal of Atmospheric and Oceanic Technology 15, 522-534.
Wunsch, C., 1998. The work done by the wind on the oceanic general circulation. Journal of Physical Oceanography 28, 2332-2340.
Zilberman, N., Merrifield, M., 2006. Internal tide generation over mid-Atlantic ridge topography. Eos Trans. AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract OS23L-03.